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Sona Transition Studies in the RHIC OPPIS[1]

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Abstract. In Optically Pumped Polarized Ion Sources (OPPIS), the atomic beam is first electron polarized, and then this polarization is transferred to the nucleus by a suitable perturbing magnetic field. In the BNL OPPIS, the electron polarized atomic beam experiences the perturbing field when it traverses a region where the axial magnetic field reverses direction in a controlled manner – strength and gradient. This is the so-called Sona Transition region, named after P. G. Sona, who first suggested the technique. We have extensively studied how the magnetic field profile in the Sona region affects beam polarization. In these studies, we have observed oscillations in polarization for certain field profiles, and tried explain them. We report on these studies.

Keywords: Optically Pumped Polarized Ion Source, Sona Transition.
PACS: 29.25.Lg.

INTRODUCTION

The Optically Pumped Polarized Ion Source (OPPIS) at BNL /1/ produces nuclear polarized H^- for the AGS and RHIC accelerators. 0.5~1.0 mA x 400 μsec and 85~90% polarized beams are routinely delivered at 35 keV. A schematic of the OPPIS is given in Figure 1. An ECR source operating at 29.2 GHz in a magnetic field of 1 T, delivers a 30~50A, 3 keV proton beam, which passes through optically pumped polarized rubidium vapor in a cell situated in a field of 2.5 T, where the protons capture polarized electrons to form an electron polarized H^o beam. The 3 keV H^o beam passes through a region where the axial magnetic field reverses direction in a controlled way, allowing the electron polarization to be transferred to the proton, using the Sona Transition technique/2/. Beyond the Sona Transition region, the H^o beam, now proton polarized, enters the Sodium Ionizer where it is ionized to polarized H^- in a field of about 1.5 kG. The polarized H^- beam is extracted from OPPIS at 35 kV, and accelerated to 200 MeV before it is injected into the Booster.

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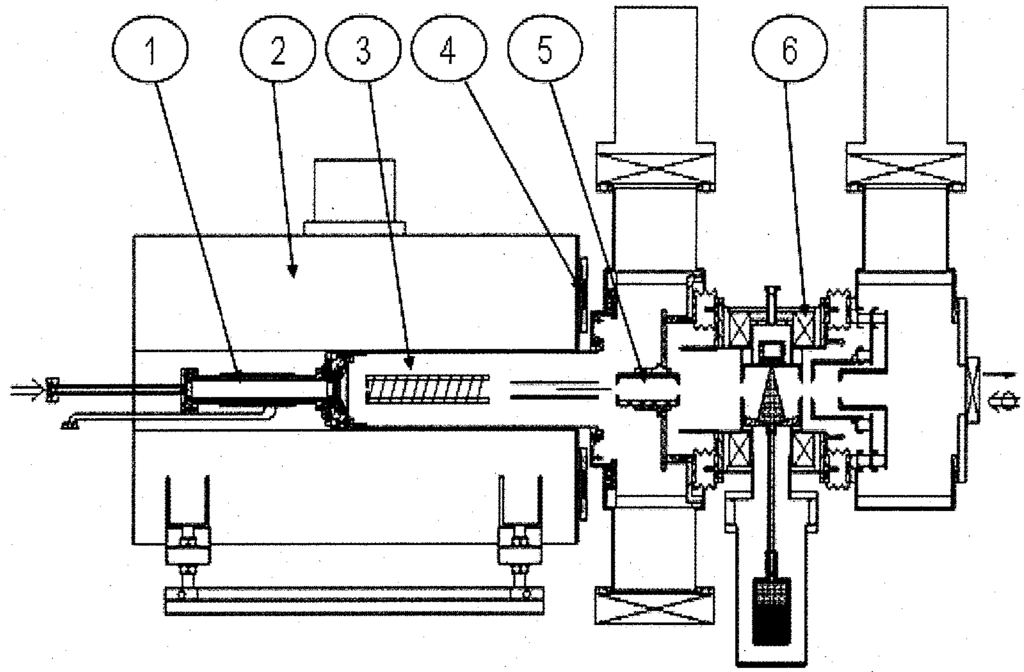

FIGURE 1. General layout of the RHIC OPPIS. 1-ECR primary proton source; 2-superconducting solenoid; 3-optically-pumped Rb vapor cell; 4-Correction Coil; 5 Sona shield; 6 –Na-jet ionizer cell. The pump and probe laser beams enter from the right and left, respectively.

THE SONA TRANSITION REGION

Figure 2 is a schematic diagram of the present Sona region. Its makeup has evolved over the years in a bid to optimize the efficiency of the Sona transition. The axial position of the Super Conducting Solenoid (SCS) can be adjusted to optimize the proton yield from the ECR; this affects the magnetic field in the region of the Sona shield. The Sona Shield (SS) and the Correction Coil (CC) can also be moved axially as suggested by magnetic field simulations of the region. The steel plate

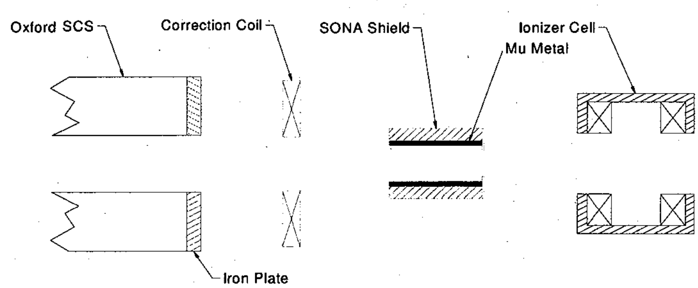

Figure 2. Schematic of the present Sona Transition region.

reduces the fringe field of the superconducting solenoid by a fixed amount. The Sona shield further shapes the field in the transition region. Varying the CC current allows one to move the zero-crossing point in the transition region. The mu-metal insert in the Sona shield reduces transverse magnetic fields inside the shield that are due to residual magnetism in the shield material.

Theory

The Breit-Rabi diagram for the ground state of hydrogen is shown in Figure 3. The beam atoms coming from the rubidium neutralizer – from the right, in this figure - have either m_J=1/2 or -1/2, depending on the wavelength of the pump laser beam. In the RHIC OPPIS, the electron polarized H^o beam is produced in a field of 2.5 T, which steadily decreases as it nears the Sona region. As long as the field changes slowly – adiabatically, in Sona's words - the atoms follow the energy levels in which they are created, i.e., 1 and 2 or 3 and 4. At a very low field, ~1 G, there is a sudden reversal of

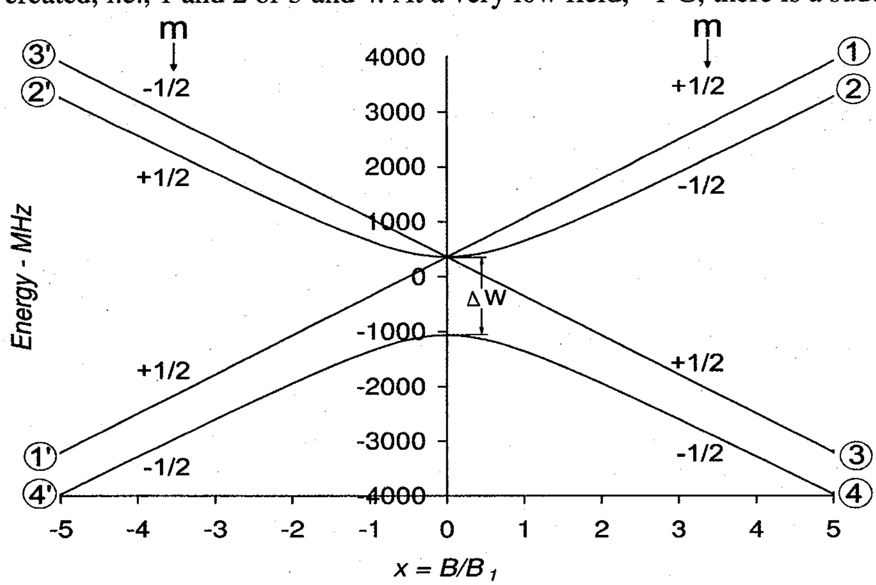

FIGURE 3. Breit-Rabi diagram of the ground state of hydrogen. The m values shown are for m_I. Frequencies are relative to 0 MHz., the 'center of gravity' of the *1S* hyperfine interval, $\Delta W \sim 1420$ MHz. $B_1 = \Delta W/[(1-k)\mu_o g_J]$ and $k = g_I/1836.1 g_J$.

the field direction to ~ -1 G. If the reversal is sudden enough, the atoms do not follow the field, and the states evolve as shown with the new field direction - negative values of x in Fig. 3.

The field goes through zero only on the axis of symmetry. Off-axis, there is a non-zero radial component, B_r, which for cylindrically symmetric fields, is given by:

$$B_r = -B_o' \bullet r/2 \tag{1}$$

The electron spin precession rate about B_r is:

$$\omega_p = e \bullet B_r /(2m) = eB_o' \bullet r/(4m) \quad (2)$$

In addition, the off-axis atoms see the field rotating about an axis perpendicular to the longitudinal axis, at a rate given by (with t = 0 at the zero crossing point):

$$\omega_B = \frac{r/2v}{(r/2v)^2 + t^2} \quad (3)$$

Sona's second condition, that the zero-field crossing be "sudden", is quantified in the relation:

$$\omega_p / \omega_B << 1 \quad (4)$$

Near the crossing point, B_r should be small ($\leq$ 1 G/cm), for ω_p to better meet the sudden crossing condition. We have measured crossing gradients $\leq$ 0.1 G/cm.

For a 3 keV H^o beam, at t = 0, and 1 cm radius, $\omega_B \sim 1.6 \cdot 10^9$ radians/s.

FIELD SCANS

Because magnetic field profiles could not be measured each time the current in CC was changed, we had to rely on simulations based on our best knowledge of the geometries of the SCS, ionizer and CC coils, and the numbers of turns of windings in their component coils/3/. The axial field profiles for the CC and the ionizer were measured (with the other device not powered) and compared with simulations. Figure 4 shows that the simulations reproduce the measured fields very well, and simulations can be used to obtain reliable field profiles in the Sona region.

A typical scan obtained with the latest configuration of the Sona region is shown in Figure 5, and the axial field profiles for some currents are shown in Figure 6.

Scans were also taken with the CC current reversed, in which case the zero crossing points were moved downstream of the SS. They show similar but much slower oscillations. The oscillations in polarization at both extremes of the scan are very reproducible and call for a physical explanation, which was suggested by Clegg/4/.

At some values of the CC current, the resulting magnetic field in the Sona Region could produce an integrated rotation of the electron spin vector, about the radial field, equal to an even multiple of 2π radians, for peaks in the polarization, and to an odd multiple of π radians for the minima. These conditions would be expected to have a radial dependence because of the radial dependence of the transverse field [1].

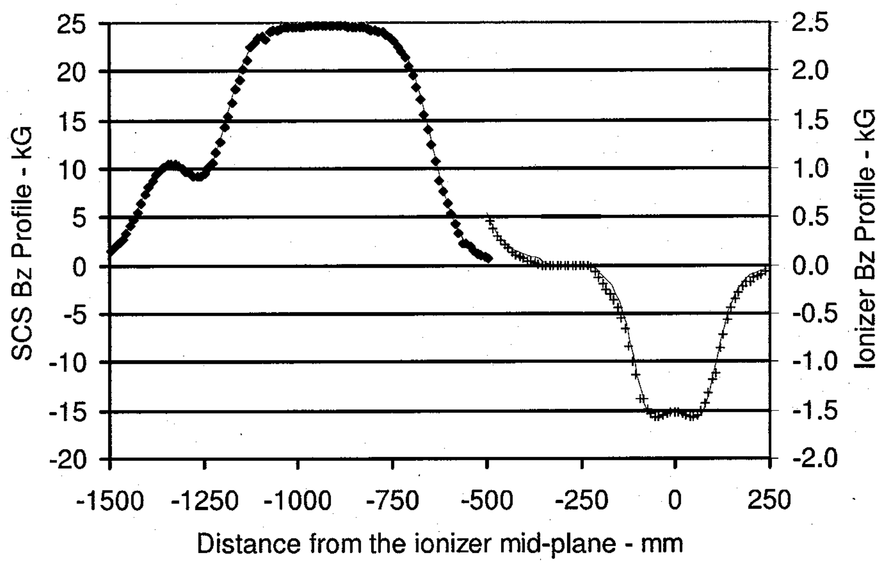

FIGURE 4. Measured axial profiles of the SCS (♦ left axis) and ionizer (+ right axis) . The calculated fits are the faint lines through these points. The axial position of the Sona region is given by the short heavy horizontal line. Note the 10-fold difference in vertical scales.

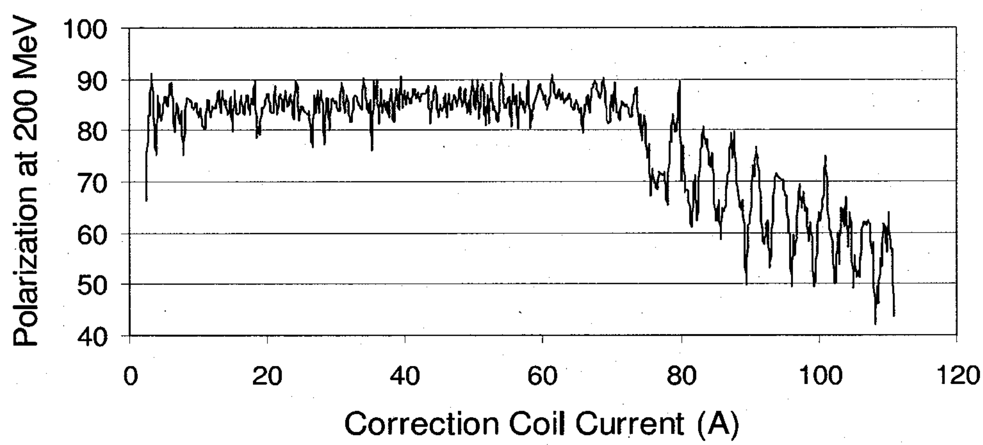

FIGURE 5. Polarization at 200 MeV vs Correction Coil Current.

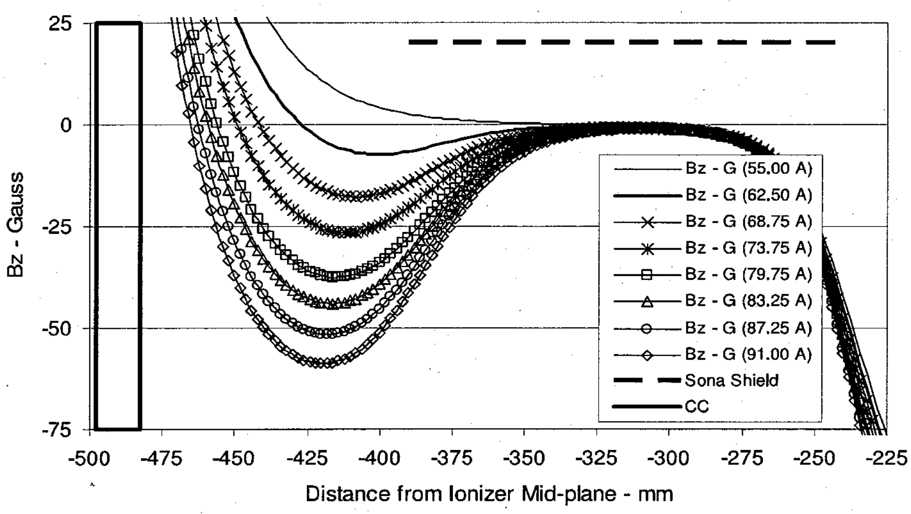

FIGURE 6. Calculated longitudinal profiles for some currents in Figure 5.

The intensity distribution of the beam would also be expected to affect the final polarization. These factors combine to produce a smooth transition from maxima to minima.

In Figure 7, we have plotted the zero-crossing slopes and the ratio of precession angle to 2π over a 5 cm distance about the zero-crossing point, at 1 cm radius for the scan and field profiles shown in Figs 5 and 6 respectively. The last four points in these plots correspond to the first 4 polarization peaks in the scan shown in Figure 4, but the angles are not clustered around integral values of 2π, as would be expected from $\pi/2\pi$ flipping of the electron spin.

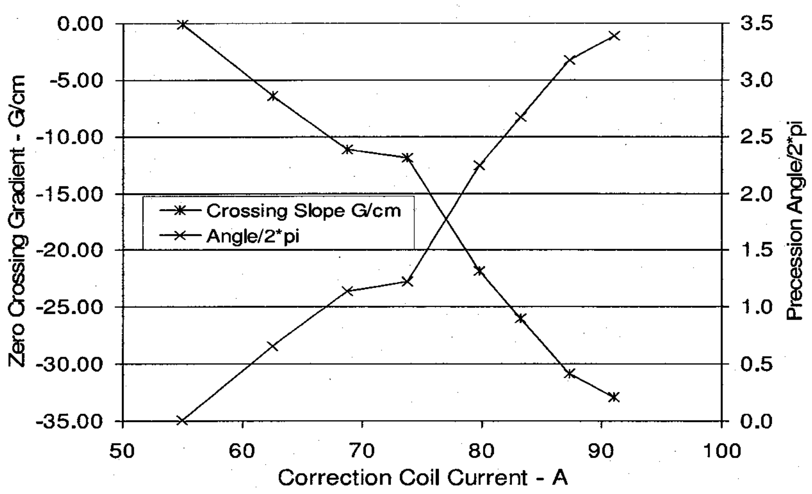

FIGURE 7. Zero-crossing slopes and precession angles for currents in Figure 5.

Simulations

It should be possible to perform computer simulations of the electron polarized atoms drifting through the Sona Region to estimate the mixing between the states, and the final polarization efficiency of the Sona Transition region. A 1968 paper by G. Ohlsen /5/ describes a computer program which could serve this purpose, but we have not been able to get it working. After the presentation of this paper at the Workshop, A. Belov of INR /6/, Moscow, informed us that he had a program which, with some modification, could be used for our simulations. We are now using a version this program, and obtaining useful results which we shall report in the future.

CONCLUSIONS

The configuration of the Sona Transition region in the BNL OPPIS has gone through several modifications to improve the efficiency of transfer of electron polarization to the protons. We have measured field gradients of less than 0.1 G/cm inside the Sona shield. As a result of this work, we estimate that the efficiency of the Sona transition is now 95 – 98%. The polarization of the H- beam is now 86-90%. In our studies we have also observed an unexpected and interesting phenomenon in which the polarization oscillates as the correction coil current is swept, and the crossing point is moved upstream or downstream of the Sona shield, depending on the sense of the current in CC. Our efforts since then have largely been directed to providing a physical explanation for this behavior. The suggestion of π and 2π flips for the minima and maxima provides a qualitative explanation. We are now simulating passage of the atoms through the transition region; we expect these to yield quantitative agreement with the observations.

ACKNOWLEDGEMENTS

We gratefully acknowledge the suggestion of Prof. Thomas Clegg of the University of North Carolina at Chapel Hill, during a visit to BNL, that π and 2π flips of the electron spin about the transverse fields could be the root cause of the oscillatory behavior of the polarization observed scans of the CC current.

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